Frequency Probe Measurements in Electron Beam Generated Processing Plasmas

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ABSTRACT

Plasma density measurements are an essential tool in understanding and controlling plasma processing across a wide range of applications. Charge collection probes (Langmuir probes) are of limited utility in depositing plasmas, high pressure applications or in processes that require the use of reactive gases, as these environments result in unreliable data acquisition. Plasma frequency probes are an attractive alternative to Langmuir probes in such applications since they do not suffer significant performance degradation in these environments. This work presents frequency probes measurements of plasma density over a range of 10^9 to 10^{12} cm^{-3} in a variety of processing plasma chemistries (N_2, CH_4, NH_3, O_2 and SF_6). This work also features frequency probe measurements of plasma potential, electron temperature, and electron energy distribution function.

INTRODUCTION

Frequency Probes

The Naval Research Laboratory is developing multiple frequency probe geometries for use as diagnostics in plasma processing systems. Plasma frequency probes operate on the principles of antenna impedance in a plasma, an area that incorporates an extensive body of research going to back to the early 1960s. [1-8] The use of impedance measurements for space physics research has been a fairly active field for some time [9-11], but there have also been new applications. Plasma frequency probes are of interest for any application where plasma parameters are difficult, or impossible to measure using a Langmuir probe; ion thrusters,[12] reactive processing plasmas,[13] and depositing plasmas are examples of environments where Langmuir probe measurements can be difficult due to their reliance on charge collection at the probe surface. Initially, interest in frequency probes grew out of a need for density measurements in harsh plasma environments; however plasma potential and electron energy distribution function [14, 15] measurements have also been made using plasma frequency probes. In this work we also present the LCR probe [16], a variant of plasma frequency probes that eliminates complications from spatial density gradients and magnetic field effects.

Electron Beam Generated Plasma Processing System

This work was performed in one of the electron beam generated plasma processing chambers at the NRL's Plasma Applications Laboratory. Electron-beam-produced plasmas differ from conventional plasma processing sources due to the fact that ionization and excitation processes in the plasma are driven by an energetic electron beam instead of low energy discharge electrons. Electron beam generated plasmas have been shown to offer high densities (10^{10} to 10^{11} cm^{-3}), low electron temperature (< 1 eV) [17, 18, 20], low incident ion energies [21], and unique gas chemistries. In addition, these plasmas represent a localized, scalable plasma source that is decoupled from the vacuum chamber geometry. The system specific to this paper utilizes a steady state hollow cathode plasma electron source to produce an electron beam which is confined to a thin, large area, sheet using an axial magnetic field. This geometry produces a high-density plasma over the volume of the beam [18,19], with decaying plasma density outside the beam volume.

EXPERIMENTAL SETUP

Processing Chamber and Electron Beam Source

The electron beam plasma processing chamber consists of a stainless steel, vacuum vessel situated within magnetic field coils that produce a uniform axial magnetic field within the confines of the vacuum chamber. Inside the chamber are the plasma processing components; the electron beam source, a movable processing stage, a termination anode for the electron beam, and the LCR probe and plasma frequency probe diagnostics mounted on linear motion feedthroughs. The frequency probe and LCR probe are connected via double shielded coaxial cable to a network analyzer providing a means to measure the plasma impedance characteristics. A diagram of the experimental setup is shown in Figure 1.

The electron source consists of a rectangular hollow cathode discharge held a few hundred volts negative with respect to an anode mesh. The anode mesh dimensions are 1 cm x 10 cm. The anode mesh is biased negatively with respect to a slotted grounded anode and serves to accelerate the electrons extracted from the hollow cathode discharge to high energy. The magnetic field confines the beam electrons to a

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sheet geometry creating a sheet - like plasma extending from anode mesh to a termination anode on the opposite end of the vacuum vessel. Further details can be found in reference [22]. For the results reported here the cathode voltage was ~1 kV.

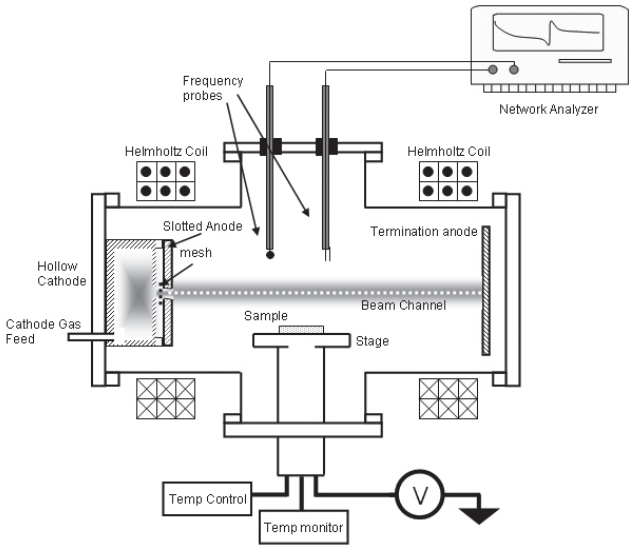

Figure 1: Diagram of the electron beam plasma processing chamber showing plasma diagnostic configuration.

FREQUENCY PROBE OPERATION AND RESULTS

When the probes are connected to the network analyzer the complex reflection coefficient of the probes, Γ, are measured and their impedance characteristics can be calculated. The presence of a plasma influences the impedance characteristics measured by the network analyzer allowing for plasma parameters to be calculated.

Antenna Based Frequency Probes at High and Low Frequency

The impedance characteristics calculated by the network analyzer are the magnitude of the complex impedance, $|Z|$, and the phase of the impedance, ϕ. Depending on the frequency regime in question these impedance characteristics can provide measurements of electron density, the plasma potential, and the electron energy distribution function.

When the network analyzer is operated near the plasma frequency, resonances correlated with the plasma frequency and sheath capacitance become visible. The sheath resonance is characterized by a low impedance resonance where the phase changes from negative to positive. Conversely the plasma frequency resonance is characterized by high impedance and a phase transition from positive back to negative. the plasma frequency resonance provides measure of n_e over the probe's sampling volume. This behavior is exhibited in Figure 2.

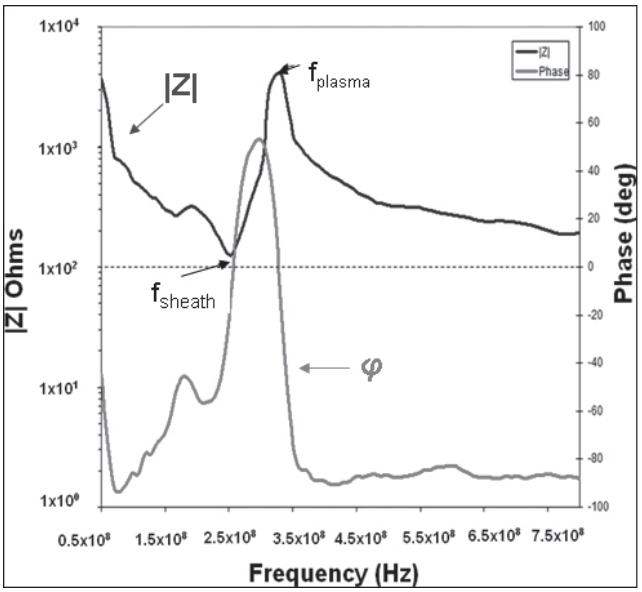

Figure 2: The impedance and phase characteristics of an Argon plasma measured by a frequency probe. The sheath resonance and plasma frequency resonance are indicated in the figure.

When the network analyzer is operated in a frequency regime far removed from these resonances ($f << f_{pe}$) it can be used to measure the AC resistance of the plasma. If a variable DC bias is applied to the frequency probe this AC resistance measurement can be used to measure $(dI/dV)^{-1}$. This is expressed in Equation (1) where R_{AC} is the AC resistance, C_{AC} is the AC capacitance I_e is the electron current V_{probe} is the DC probe bias and $\mathrm{Re}(Z_{AC})=|Z|\cos(\phi)$.

$$\mathrm{Re}(Z_{AC})=\frac{R_{AC}}{1+\omega R_{AC}C_{AC}}\cong R_{AC}\cong\left(\frac{dI_e}{dV_{probe}}\right)^{-1} \quad (1)$$

As probe bias is varied, the plasma potential, ϕ_{plasma}, is indicated by a minimum in R_{AC}. From the plasma potential the electron energy distribution function can be found using the technique outlined by Druyvesteyn [23]. Where $E=\phi_{plama} - eV_{probe}$, m=electron mass, and A_p = probe area.

$$f(E)=\left(\frac{4}{e^3A_p}\right)\sqrt{\frac{mE}{2}}\left(\frac{dR_{AC}^{-1}}{dV_{bias}}\right) \quad (2)$$

The application of this technique is shown in Figure 3.

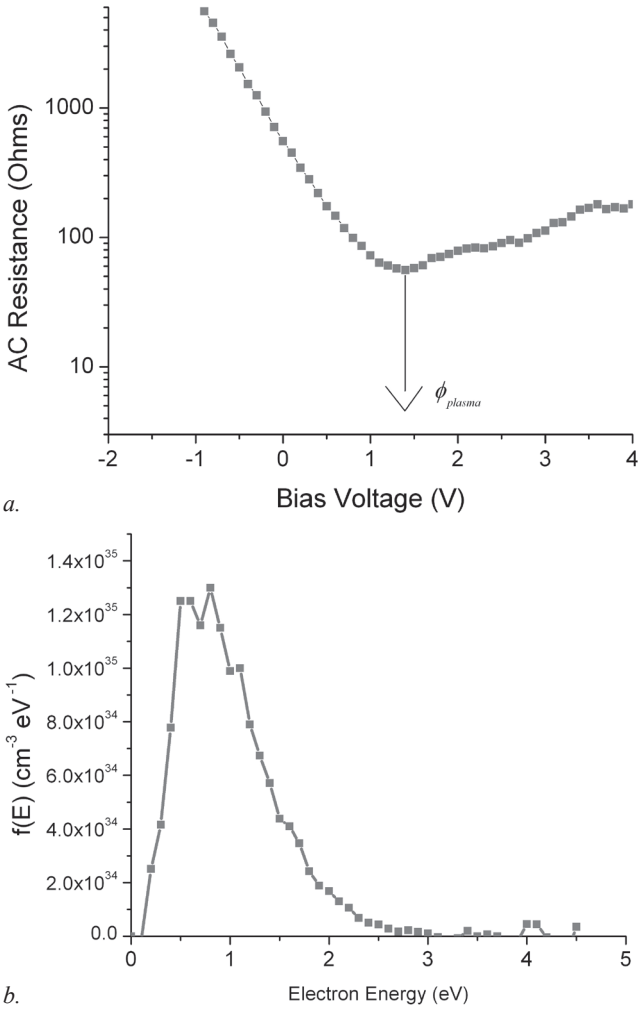

Figure 3: (a) R_{AC} as function of bias voltage illustrating the minimum at the plasma potential (1.2 V). (b) Applying equation (2) to the data in 3a, an EEDF for the plasma can be reconstructed showing $<E_{av}>=1.1$ eV and $n_e=2.5x10^{10}$ cm^{-3}.

The LC Resonance (LCR) Probe

A shortcoming of antenna-based frequency probes is that they are unable to measure the plasma frequency directly when a magnetic field is present. Instead, the upper hybrid frequency is measured requiring accurate knowledge of the local magnetic structure for plasma density to be calculated [5]. The LC Resonance probe [16], or simply LCR probe, is a variant of the frequency probe. The LCR probe is constructed by terminating a semi-rigid coaxial cable with a small capacitor consisting of two parallel metallic plates (or mesh), one connected to the center conductor and the other to the outer shield of semi-rigid coaxial cable.

The LCR probe is based on the following principle: any short ($l << \lambda$ where l is the characteristic length scale of the probe), non-resistive object can be represented as capacitive and inductive elements in series. The capacitive components C account for charge stored on the object and dominate at low frequency. The inductive components L account for current flowing through the object and dominate at high frequency. At the resonance frequency ω_R, the two effects cancel such that the total impedance, Z,

$$Z = i\omega L + \frac{1}{i\omega C} \tag{3}$$

is zero, and therefore

$$\omega_{R0} = \frac{1}{\sqrt{LC}} = \left(\frac{d}{LA\varepsilon_0} \right)^{1/2} \tag{4}$$

The introduction of a plasma between the plates will alter the relative dielectric constant, $\varepsilon_p(\omega)$, thus shifting the resonance frequency to

$$\omega_R = \left(\frac{d}{LA\boldsymbol{\varepsilon_p}\varepsilon_0} \right)^{1/2} \tag{5}$$

If the LCR probe is properly constructed, ω_{R0} can be tuned such that $\omega_{R0} >> \omega_{ce}$, where ω_{ce} is the electron-cyclotron frequency, in this case magnetic effects can be ignored and plasma density can be easily calculated from the shift in the resonant frequency. The method for calculating the density is shown in Equations (6a) and (6b). (6a) calculates the density without accounting for the sheath around probe, whereas (6b) adds a simple vacuum sheath correction to density calculation, where d is the plate separation and s is the sheath thickness.

$$n_e = \frac{m_e \varepsilon_0}{e^2} \left(\omega_R^2 - \omega_{R0}^2 \right) \tag{6a}$$

$$n_e = \frac{m_e \varepsilon_0}{e^2} \left(\frac{\omega_R^2 - \omega_{R0}^2}{1 - \frac{2s}{d} \left(\frac{\omega_{R0}}{\omega_R} \right)^2} \right) \tag{6b}$$

The resonance frequency shift and its use in measuring a plasma density profile in an electron beam generated plasma are shown in Figure 4. Further details on LCR probe theory and application can be found in reference [16].

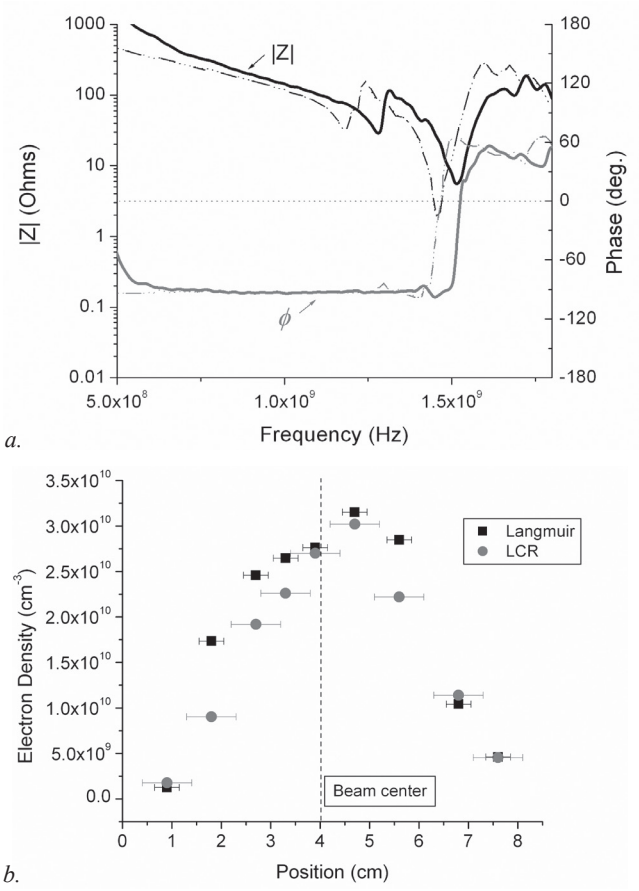

Figure 4: (a) The shift in the resonant frequency of an LCR probe induced by a 3.5x10^9 cm^{-3} Argon plasma (b) A spatial plasma density profile measured with an LCR probe and a Langmuir probe (Profile taken in Argon at 10 mTorr with a 1 kV cathode voltage).

CONCLUSIONS

Plasma frequency probes have proven to be a good alternative to Langmuir probes for measurements of n_e, T_e, and ω_{plasma} over a wide range of conditions. In addition frequency probes are able to perform density measurements in depositing plasmas and reactive gas plasmas where Langmuir probes are in-effective. Complications to frequency probe density measurements in magnetic fields have been overcome using the LC Resonance Probe. The LC Resonance probe provides a local plasma density measurement and is un-affected by the presence of magnetic fields. Our work has shown good agreement between LCR probe and Langmuir probe measurements over a wide range of plasma conditions. Future areas of research include exploring reactive gas plasma parameters with frequency probes and performing plasma density measurements with the LCR probe in magnetron sputtering discharges.

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